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A Comparison of Low-Velocity Impact and Quasi-Static Indentation

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14. ABSTRACT The purpose of this investigation is to assess the potential interchangeability of key material response metrics as measured using quasi-static indentation (QSI) and low-velocity impact (LVI). This report compares the response of a S2/SC-15 glass /epoxy composite material subjected these two test methods. Specimens of 102 × 152 × 5.5 mm were quasi-statically indented at load rates in the range of 1.2 to 50 mm/min. Differences in material response over this range of loading rate were found to be negligible. The average value of peak input energy calculated from these QSI tests was used as the impact energy for subsequent LVI tests of identical specimens. Material tested using LVI (3.41 m/s velocity) exhibited higher initial stiffness and absorbed energy but with slightly lower maximum force and displacement values compared to material tested with QSI. Thirty QSI and LVI specimens were then evaluated with compression after impact (CAI) testing, and all specimens exhibited equivalent CAI strengths. Lightbox and cross-section analyses showed that material tested under LVI exhibited significantly less delamination and significantly more intralaminar fracture compared to QSI. For these reasons, LVI and QSI data are not interchangeable for this material system.						
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1. Introduction

Despite the great benefits that composite materials confer by way of their high strength-to-weight ratio, they remain vulnerable to damage from low-velocity impact (LVI). Impact may cause any combination of damage modes including fiber crushing, delamination, through-thickness shear fracture, and perforation.

The LVI (American Society for Testing and Materials [ASTM] D7136) and compression after impact (ASTM D7137) tests (*1*, *2*) are well-known methods for assessing the damage tolerance of relatively thin (5–6-mm) composite laminates to single impacts (6.7 J per millimeterof thickness). These methods have been used for decades in developing and evaluating aerospace composites.

The use of quasi-static indentation (QSI) techniques has been suggested in the literature as a method that is interchangeable (vis-à-vis the quantification of material damage) with LVI. In his comprehensive review of research on impact testing for contemporary composite materials, Feraboli (*3*) observed that QSI and LVI testing are generally accepted in the literature as interchangeable. Indeed, in the present authors' review of the literature, many studies (e.g., references *4* and *5*) show good agreement between QSI and LVI test results, particularly in the form of force-displacement data. In contrast, other research has concluded that the interchangeability of these two methods is limited by differences in peak load and/or damage area (*6*) or is confined to certain portions of tests (i.e., loading/unloading), certain layups, or ratios of specimen span/thickness (*7*). Elber found that QSI is useful for a more thorough assessment of impact damage and preliminary material screening (*8*). However, all of the aforementioned research used different experimental methods, equipment, aperture shapes and sizes, ply counts, support spans, and materials. These references also report on carbon fiber fabrics and epoxy matrices, whereas the subject material in the present work is S2 glass woven fabric with an SC-15 toughened epoxy matrix. The U.S. Army Research Laboratory has explored the correlations between the LVI and QSI test methods as a means of developing new techniques for structures of broader interest to impact performance.

2. Objective/Approach

The objective of the work described in this report is to gain insight into the similarities and differences in several traditional performance metrics of S2-glass weave/epoxy composite laminates tested using LVI and QSI. Such knowledge will inform future experiments for assessing the damage behavior and tolerance of these important structural materials.

The approach is to first perform displacement-controlled QSI testing on composite material plaques using the fixturing and load cell from the impact tower. The value for peak deflection during QSI testing (6.08 mm) was chosen based on prior results of LVI testing using the S2/SC-15 material system. The energy, *E*, during QSI testing is calculated from the force, *F*, and displacement, *dx*, data using equation 1. This calculated energy is then used to set the mass and height of the impactor for subsequent LVI testing.

$$E = \int F dx \; . \tag{1}$$

Prior to the implementation of the approach just described, a different approach was considered wherein QSI testing would be conducted based on a target energy level. The attractiveness of such an approach is based on the idea that a universal target energy level could be set prior to conducting any QSI or LVI testing. Such an approach, however, would require real-time numerical integration of the force and displacement data and a scheme for implementing control (essentially reversal) of the load frame upon arriving at the target energy level. Unfortunately, no such control routine is known to exist in the commercial software used to control the quasi-static load frames. As such, the benefits of being able to set a precise desired energy level were outweighed by the level of effort required to implement such an approach, and it was abandoned.

3. Experimental

3.1 Material

A large "parent" panel was fabricated using eight plies of plain weave 813 g/m^2 (24 oz/yd^2) S2 glass fabric (BGF Industries, Greensboro, NC) with SC-15 (Applied Poleramic Inc., Benicia, CA) toughened epoxy matrix. Panels were laid up with a quasi-isotropic fiber architecture $[(\pm 45)/(0/90)]_{2S}$ and infused using SCRIMP (Seeman Composites Resin Molding Process). The resultant panel was 5.5 mm thick, the fiber volume fraction measured 48.3%, and the void fraction was 1.2%. All samples for the QSI and LVI tests were cut to a 102- × 152-mm area using a water jet.

3.2 Quasi-Static Indentation

QSI testing was conducted using an Instron 1125 (Instron, Norwood, MA) load frame and fixturing, as shown in figure 1, and compliant with ASTM D7136—the same fixturing used for LVI testing as described in the next section. A load cell with 90-kN capacity was used, and force was recorded at 10 Hz. The hardened steel indenter was 15.88-mm in diameter, with a hemispherical tup. Samples were clamped to the fixture at the corners and indented to the target displacement of 6.08 mm, with the load frame in displacement control.

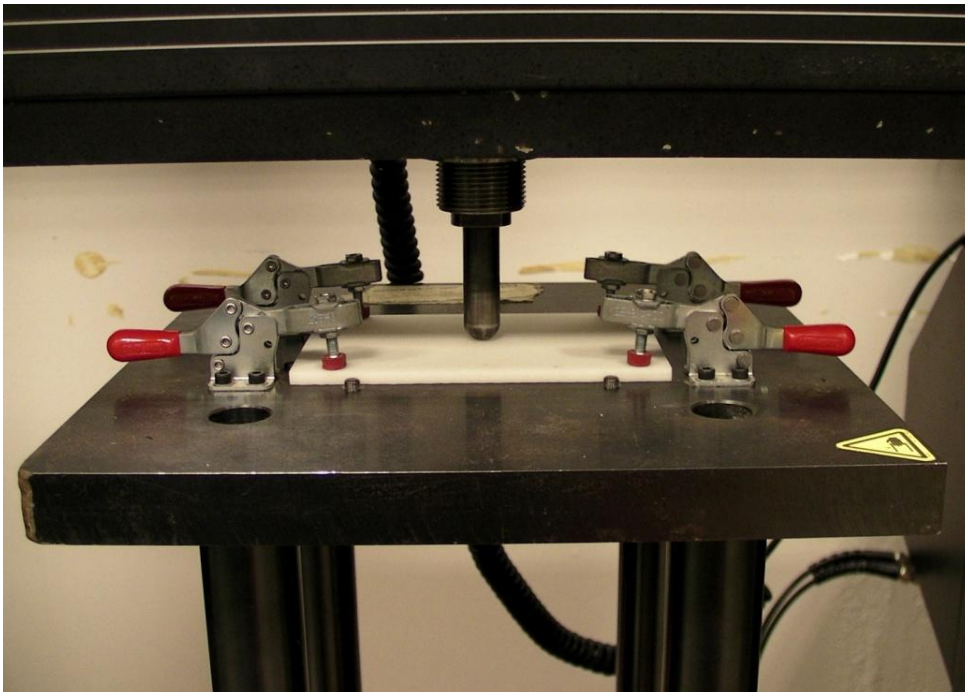

Figure 1. Instron load frame with QSI test setup.

Five different loading rates within the limits of the load frame (1.2, 2.5, 10, 25, and 50 mm/min) were used to assess the rate sensitivity of the material. The peak energy level was calculated for five samples in each test condition using equation 1. The average energy value for the 25 samples (30.7 J) was then used as the target energy for subsequent testing of samples under LVI.

3.3 Low-Velocity Impact

LVI testing was conducted using ASTM D7136 with a Dynatup 8200 drop tower and the same fixturing and impact tup described in section 3.2. A load cell with 45-kN capacity was used, and instantaneous force data were recorded during impact at 163 kHz. Specimens were impacted with a mass of 5.283 kg at 3.41 m/s velocity (30.7 J of energy).

Figure 2 shows a log-scale visualization of typical displacement rate regimes for QSI, LVI, and ballistic impact. The specific rates for the QSI and LVI tests conducted in the present work are indicated by "O" symbols.

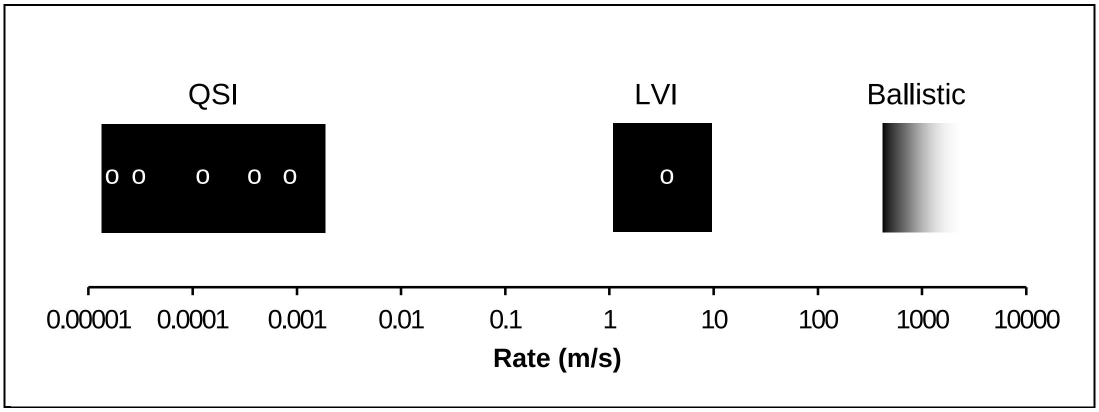

Figure 2. Illustration of displacement rate regimes for different impact test methods.

3.4 Compression After Impact

Compression after impact (CAI) testing was performed on five LVI samples and five samples of each QSI test condition using ASTM D7137. This test measures the residual strength of the damaged material after impact.

3.5 Damage Area and Dent Measurement

Damage areas and residual dent profiles were measured on four LVI samples and three QSI samples from the 2.5-mm/min test condition. Damage area was determined by digitally photographing the specimens on a lightbox. The software package "ImageJ" [XX] was used to process the digital images and quantify the delamination area. Dent profiles for these samples were measured using a Taylor Hobson "Form Talysurf Series 2" profilometer. Dents were measured ~2 h after the LVI and QSI testing to minimize effects of material creep on the measurements.

3.6 Cross-Section Photography

The samples used for damage area and dent measurements were subsequently cut in half using a water-cooled diamond saw. After the samples were oven-dried, liquid dye penetrant was applied to the plane of the cut in order to visually highlight the pattern of cracks. The crack patterns were recorded with digital photographs.

4. Results/Discussion

Table 1 summarizes the peak energies measured during QSI testing. Each entry in the table represents the average of five specimens at each rate condition. The average peak energy from this table is calculated as 30.7 J, and this average peak energy level was used for the subsequent impact tests.

Table 1. Maximum energy measured during QSI tests, average of five samples at each rate.

Rate (mm/min)	**Peak Energy (J)**
1.2	30.46 ± 0.64
2.5	30.44 ± 0.49
10	30.58 ± 0.91
25	30.88 ± 0.54
50	31.61 ± 0.65

4.1 Low-Velocity Impact

Five test specimens were impacted at 30.7 J. The force vs. displacement and energy vs. displacement plots (figures 3 and 4) provide a visual record of the repeatability of the LVI method.

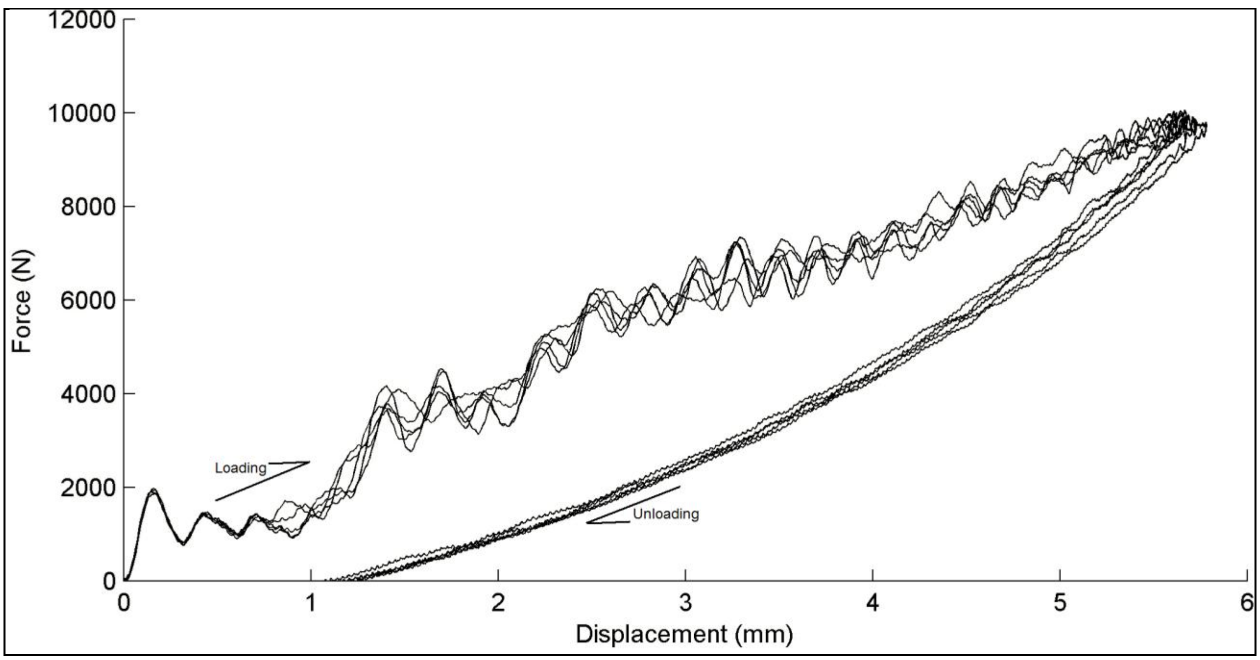

Figure 3. Impact force vs. displacement for 30.7-J LVI (ASTM D7136) of five identical S2/SC-15 102- × 152-mm, eight-ply, quasi-isotropic samples. Data is presented to show consistency in specimen response.

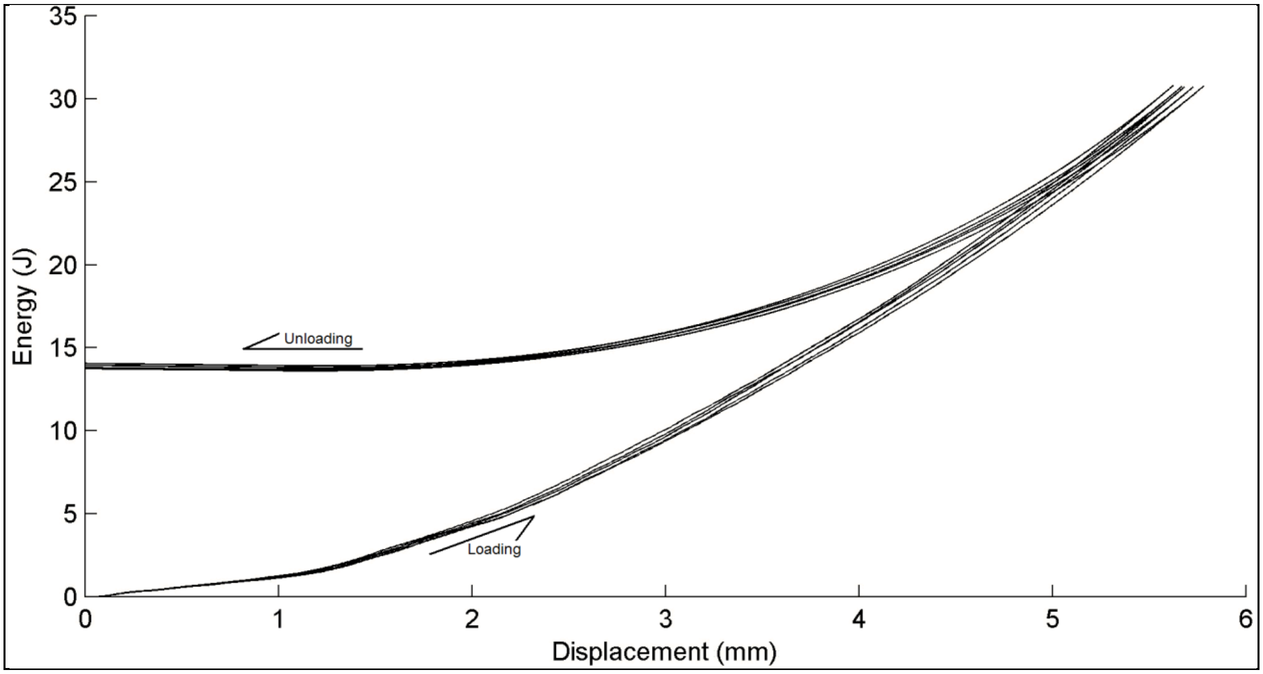

Figure 4. Impact energy vs. displacement for 30.7-J LVI (ASTM D7136) of five identical S2/SC-15 102- × 152-mm, eight-ply, quasi-isotropic samples. Data is presented to show consistency in specimen response.

4.2 LVI-QSI Comparison

Figure 5 shows a comparison of the force-displacement data collected during QSI and LVI testing. In this plot, every data set is an average of five samples per condition. Compared to the material response under any rate in the QSI tests, the material under LVI exhibits a greater initial stiffness but ultimately reaches lower values of maximum load and displacement. The inset in figure 5 shows the residual displacement at zero force for all samples. It appears that LVI samples exhibit the largest values of residual displacement despite the fact that samples tested under LVI sustain lower values of peak displacement than samples tested under QSI. Recovery of residual indentation (due to viscoelastic relaxation) was not monitored for any samples.

The force level at which damage initiates is commonly reported for QSI and LVI samples and is indicated by an inflection point in the load history. Figure 5 shows that this inflection point appears at ~4000 N for QSI samples and ~6000 N for LVI samples. This specific metric may have more significance for thin-section aerospace composite applications than thick-section, Army-relevant composites but is nonetheless another illustration of the differences in material response at the different loading rates.

The plot of energy vs. displacement shown in figure 6 indicates apparent differences in the energy absorption response of the material under the two testing conditions. Considering that a peak energy of 30.7 J was put in to all samples, the QSI samples returned ~20 J and the LVI samples returned ~16 J.

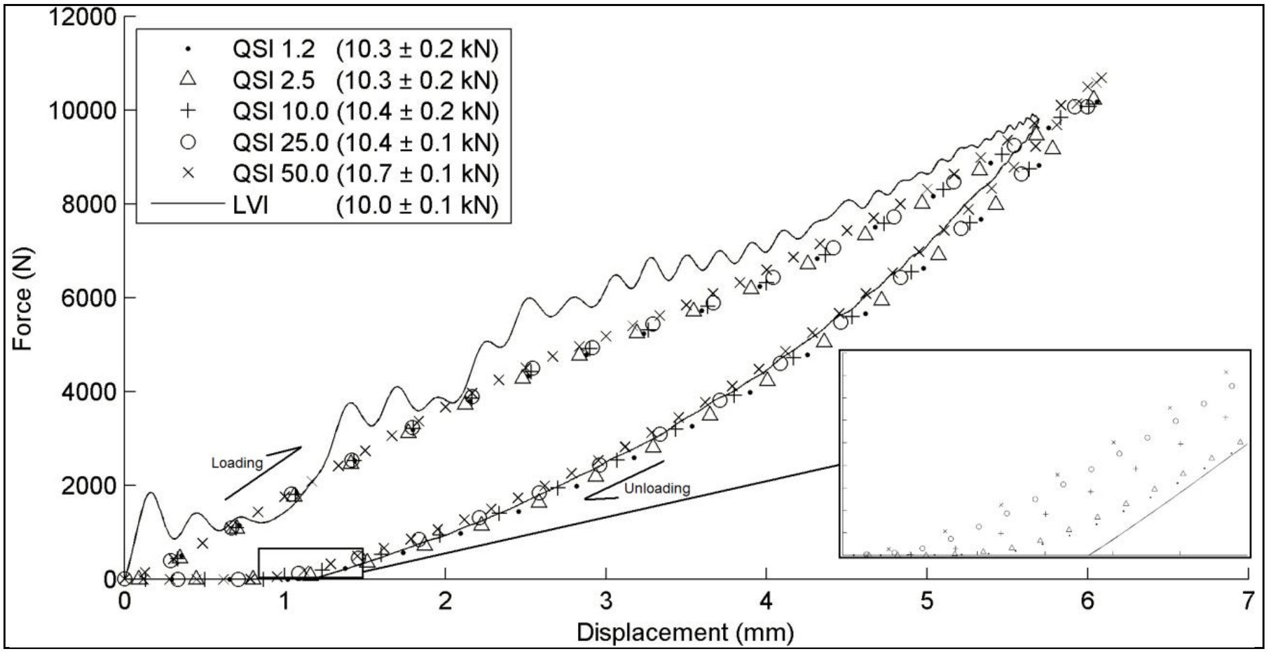

Figure 5. Force vs. displacement comparison of QSI and LVI data for S2/SC-15 eight-ply, 102- × 152-mm, quasi-isotropic samples. Each data series represents an average of five tests. LVI results in slightly lower peak force and displacement than QSI. The LVI data also shows greater residual displacement at zero force (see inset).

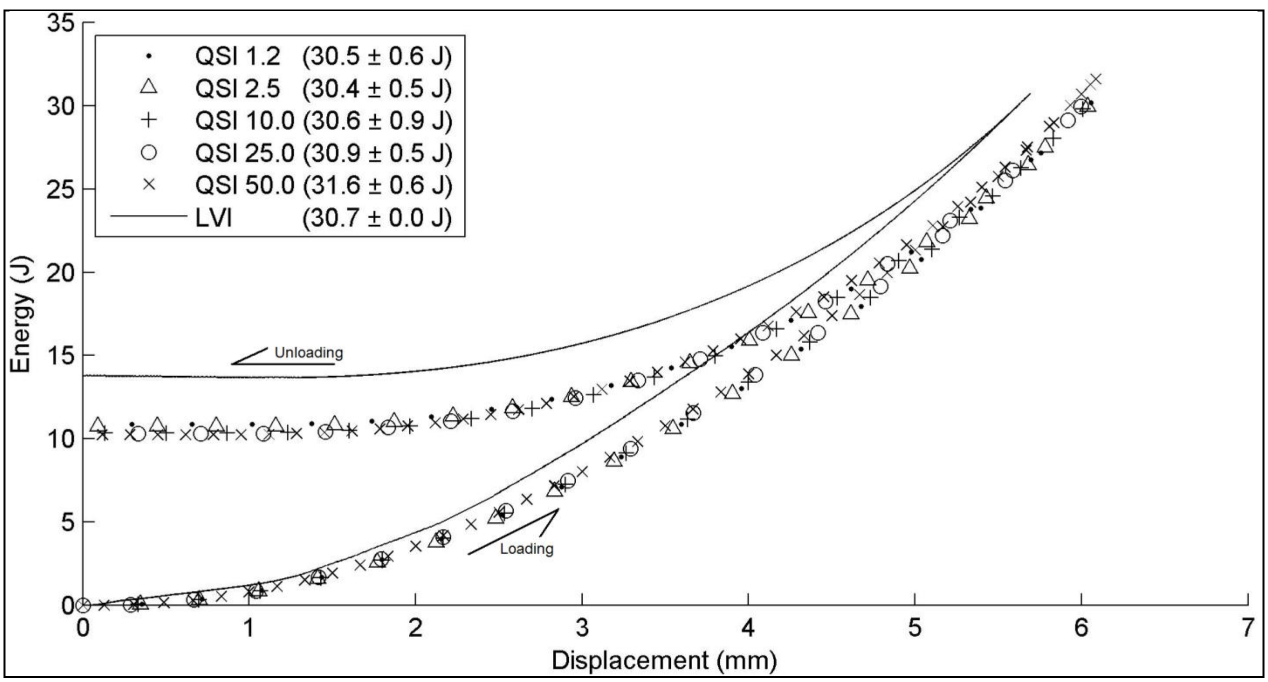

Figure 6. Comparison of energy vs. displacement for QSI and LVI data for S2/SC-15 eight-ply, 102- × 152-mm, quasi-isotropic test samples. Each curve shows an average of five tests. The LVI data shows 36% greater energy absorption than QSI. The LVI data also shows a lower peak displacement than QSI.

4.3 Compression After Impact

Results from CAI tests of all post-damaged samples are shown in figure 7. In this figure, each data set represents the average of five samples per test condition. Samples that were tested under LVI exhibited a slightly stiffer response during compression compared to samples that were tested under QSI. All samples failed at essentially the same stress level.

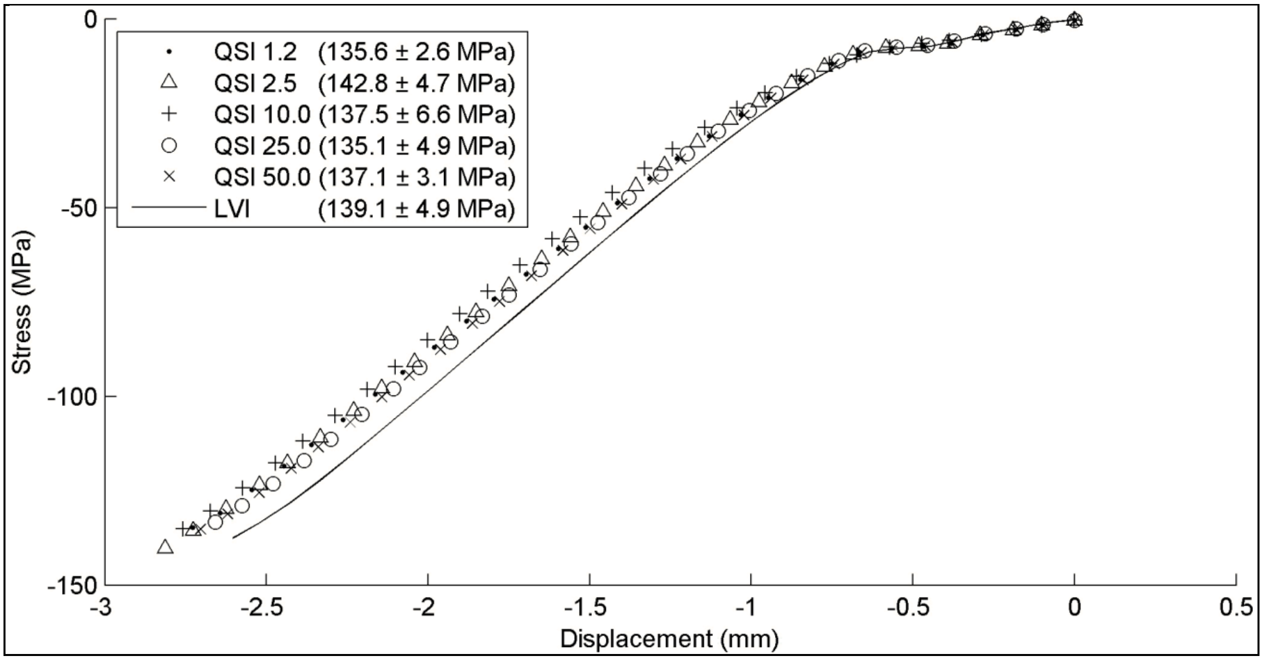

Figure 7. Comparison of stress vs. displacement for CAI of S2/SC-15 eight-ply, 102- × 152-mm, quasi-isotropic test samples. Each curve shows an average of five tests. LVI-tested samples were slightly stiffer under compression, while both QSI and LVI samples failed at a similar stress level.

4.4 Damage Area and Dent Measurement

Damage areas measured using a lightbox showed that material tested with QSI exhibited larger delamination areas compared to material tested with LVI, as shown in figure 8. Dents in the material samples show that material tested using QSI also exhibits a larger permanent dent compared to material tested with LVI. QSI samples 46, 47, and 48 were all indented to a maximum displacement of 6.08 mm, as described in section 3.2. Because the LVI samples only exhibited an approximate displacement of 5.71 mm (as shown in figures 5 and 6), it was decided to investigate the effect of limiting the maximum displacement of QSI samples 52 and 53 to 5.71 mm. Figure 9 shows that even at this reduced maximum level of indentation, the dents were still 3× greater than the dents in material tested with LVI to the same maximum displacement.

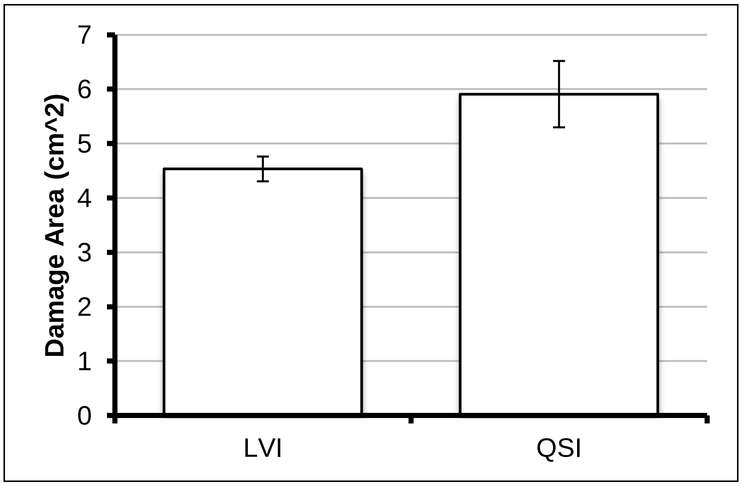

Figure 8. Delamination areas measured using a lightbox, showing that QSI imparted 30% more delamination to the samples.

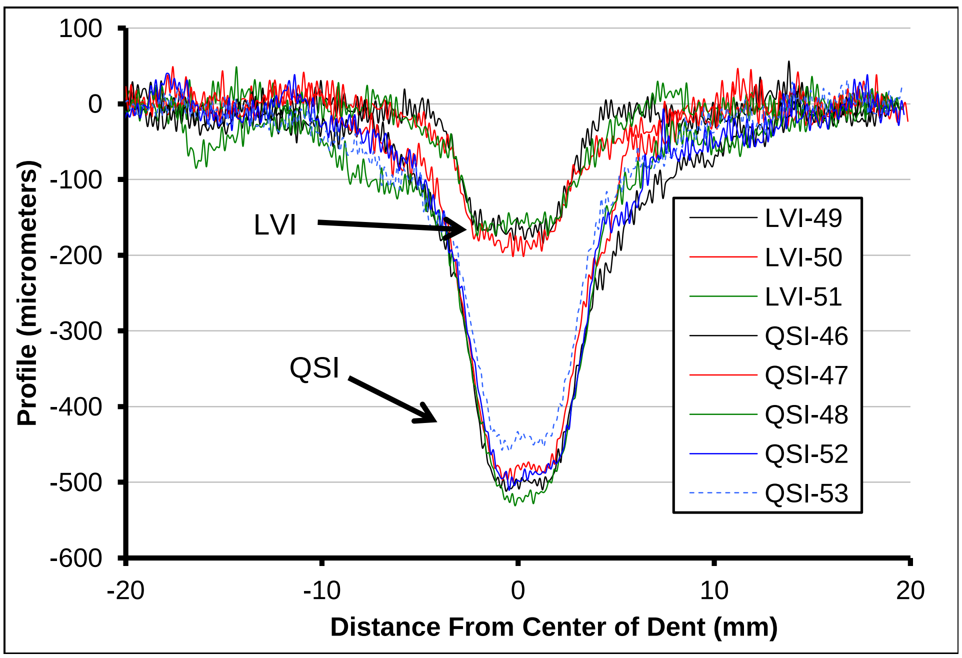

Figure 9. Profile measurements across the dent for LVI and QSI samples. Dents in QSI samples were approximately 3× greater than the dents in LVI samples.

4.5 Cross-Section Photography

Figure 10 shows photographs of cross sections of LVI and QSI samples wherein the cracks were highlighted with dye penetrant. Material tested under LVI exhibits significant intralaminar fracture (vertical cracks within the layers) in addition to interlaminar fracture (horizontal cracks between layers). This is consistent with findings in the literature wherein the fracture energy of rubber-toughened epoxies exhibits significant weakening with increasing strain rate (*9*). Material tested with QSI exhibited significant interlaminar fracture but almost no intralaminar fracture.

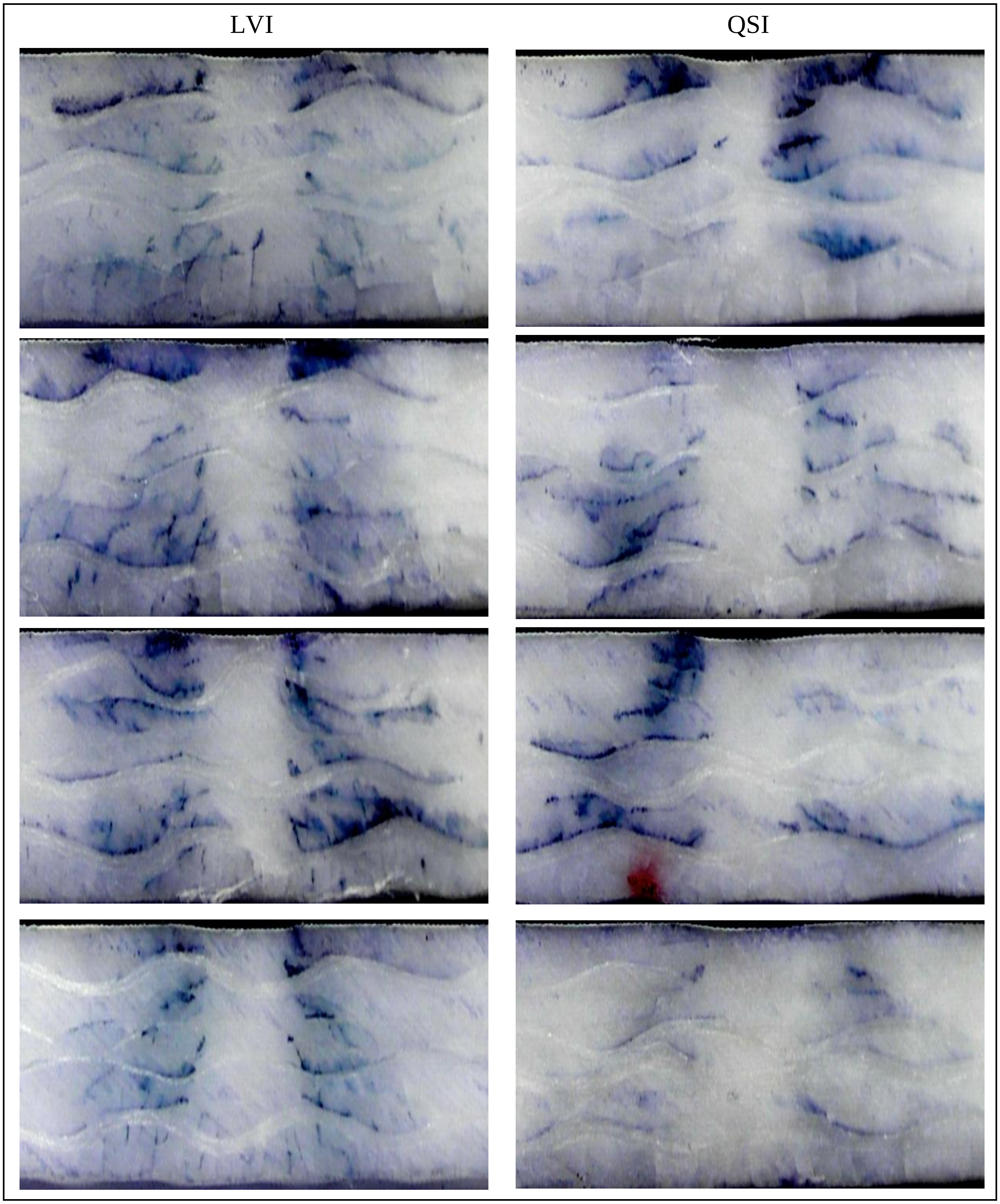

Figure 10. Photographs of cross sections of LVI and QSI samples with dye penetrant showing that LVI causes significant intralaminar fracture (vertical cracks within the layers) that is essentially not observed in material tested with QSI.

5. Conclusions

The present research finds that low-velocity impact and quasi-static indentation methods do not result in data (damage metrics) that are interchangeable for the S2/SC-15 material system. Compared to QSI, material tested under LVI sustains significantly less interlaminar delamination, as evidenced by the damage area measurements (lightbox). As well, material tested with LVI exhibits significant intralaminar fracture, as evidenced in the cross-section images. This change in material response is manifested in moderately increased apparent sample stiffness and energy absorption. The fact that both LVI and QSI result in essentially identical compression-after-impact/indent strengths further shows the confounding effects of different damage modes on the apparent damage tolerance of this material system.

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